2079

Collisions between two dimensional quadratic spatial solitons in PPLN

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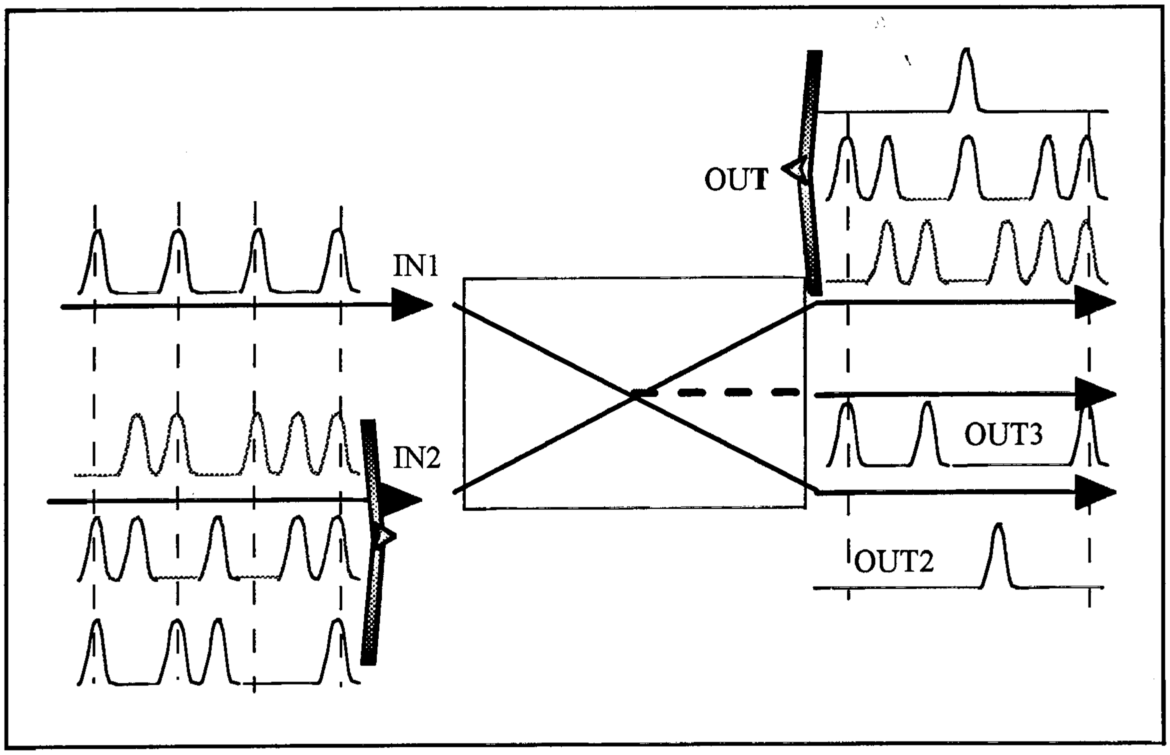
ABSTRACT

Self-guided waves (spatial solitons) that can be excited in quadratic nonlinear media have been extensively studied for their potential applications in ultra-fast all-optical processing. We have previously reported the use of solitary waves collision in a KTP crystal to experimentally demonstrate all-optical switching of infrared picosecond pulses [1,2]. Up to now, the intensity required to obtain self-trapping of a beam remained at a high level. This has been due to the lack of nonlinear crystals which combine the attributes of a large nonlinearity and phase-matching capability at experimentally convenient wavelengths. The availability of Periodically Poled Lithium Niobate can circumvent this difficulty. Two-dimensionnal spatial solitary waves in PPLN have been predicted theoretically and simulated numerically. In this communication we will report their experimental observation and for the first time their interaction in a 15mm long crystal. Then we will compare solitary wave behaviour in KTP and PPLN, in particular self-trapping intensity threshold versus phase mismatch. We will also compare experimental data with the results of our computations modelling. In a last part we will show our first experimental results about 2D quadratic soliton collision in a PPLN crystal. Finally we will discuss the advantages of choosing PPLN to realise all-optical devices using solitary wave interactions.

INTRODUCTION TO SOLITON BASED SWITCHING

In the field of information technology, nonlinear effects are seen as a possible route to developing all-optical processing devices with important consequences for optical communications systems. The aim of the project was to show that all-optical devices based on quadratic nonlinear media can in some case overcome the performances of their third-order counterparts, in particular in view of the realisation of fast time domain commutation. More specifically we have studied the possibility of information routing in a second order nonlinear crystal by exploiting self-induced waveguiding and Y-junctions as a result of soliton-soliton interaction. The nonlinear propagation phenomena that have been investigated here can lead to an all-optical device able to selectively route time multiplexed data that are included in a WDM communication stream, as illustrated below (Figure-1). The "collision" in time and space of the switching pulse with the signal pulse, both at $\lambda 3$, modifies the trajectory of the two pulses that are redirected on a common output port OUT3. When signal and switching pulses are not synchronised, they remained unchanged by the optical gate and exit the device at port OUT1 and OUT2 respectively. The signal inputs at a wavelength that differs from the switching command are left unchanged by their propagation through the routing device. Changing the frequency of the switching pulse train makes possible a different selection of data among all the inputs.

Figure 1 : Schematic set-up showing the selective routing of data in a time and wavelength multiplexed data flow, that can be performed through quadratic spatial soliton collision



IN1 : switching pulse train at λ3
IN2 : signal input constituted by the combination of several time multiplexed signals with different optical carrier frequency λ1, λ2, λ3 (wavelength and time domain multiplexing)
OUT1 : λ1and λ2signals unchanged plus the remaining part (unswitched) part of the signal at λ3
OUT2 : remaining part of the switching pulse train
OUT3 : switched part of the input signal at λ3

In the past ten years it was proved both theoretically and experimentally that cubic spatial solitons can be exploited to achieve fast all-optical processing of optical data. Taking benefit of the quasi-instantaneous response of Kerr type nonlinearity transient waveguides were generated by spatial solitons into homogeneous nonlinear materials. It was also possible to modify at ultrafast speed the geometry of the waveguides thanks to the various interactions that may occur between soliton beams: couplers for signal splitting or combining and switches were realised using parallel solitons coupling or solitons collision and fusion. It was recently shown theoretically first and then experimentaly that spatial solitary waves propagation can take place also in crystals exhibiting a substantial quadratic nonlinearity. This opened up new hopes on the use of soliton in optical processing. It was demonstrated that quadratic spatial solitary waves (QSSW) are stable even in the case of bulk propagation (2D-QSSW) on the contrary to their cubic counterparts. Moreover the advent of new materials, some of them of organic type, with high nonlinear coefficient lets expect that the self-guiding power threshold could be decreased below the above mentioned value for cubic spatial solitons. As it happened for interactions and collisions between kerr-type solitons, those between QSSWs are expected to offer the same promising field of applications.

TIME DEMULTIPLEXING IN A KTP CRYSTAL USING QUADRATIC SPATIAL SOLITON COLLISION

In this part we report the first experimental investigation on the collision between two dimensional QSSWs in a KTP crystal. In the experiment we were looking for the collision between two orthogonally polarised QSSWs. We injected, in the 2 cm long KTP crystal, two short pulses (45 ps in duration) focused into two narrow beams (FWHM 34 μm) at 1064 nm wavelength. Two QSSWs are then generated inside the KTP crystal after a very short propagation distance. Moreover, in the experiment, the beam separation, ***s***, at the input is kept fixed and equal to 100 μm, while their incidence angle is varied in a symmetrical fashion (let's say +Θ for beam 1 and -Θ for beam 2). Similarly to the scalar case and as numerically predicted for the 1D case, we found that, if the interacting angle is less than a critical value Θc =0.4° the two QSSWs fuse to generate a single QSSW; on the contrary, if Θ > Θc they pass through each other. As a consequence we have proved experimentally that inelastic and quasi elastic collisions are both possible for QSSW, depending on the "velocity" of the collision. Note that, in the experiment, we did not arrange any control for the phase relationship between the two input beams and this points out that the collisions does not rely on the relative phase between the interacting QSSWs, but only on their incidence angle and on their relative intensities. We also present the results of a numerical analysis showing satisfactory agreement with the experimental results.

The experimental set-up (see Figure-2) started with a Q-switched mode-locked Nd:YAG laser delivering 45 ps pulses at 1064 nm. Then a series of lenses, ending with a converging lens of 2 cm focal length, focused the laser beam into a bright spot of 34 μm width (FWHM) on the input face of a AR coated KTP crystal. The nonlinear crystal (Cristal Laser) 20 mm in length was oriented close to perfect phase matching for SHG. As an initial experiment we have checked the single 2D QSSW formation. For an intensity threshold of approximately 14 GW/cm^2 the two fundamental components and the generated second harmonic mutually trapped each other leading to the formation of a single 2D QSSW, stable and compressed in width at the output with respect to the linear regime[3].

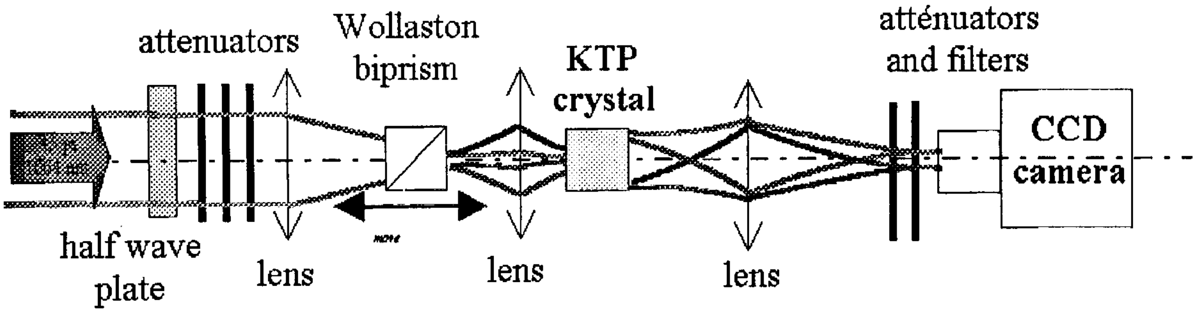


Figure 2 : experimental arrangement

A Wollaston prism (WP) preceded by an half-wave plate was further introduced before the focusing lens. The birefringent prism divided the laser beam into two orthogonaly polarised beams with angular separation of 0.3°. The half-wave plate served to adjust the intensity of the two beams at an equal level. The orientation of the Wollaston prism with respect to the KTP birefringent axis was such that each beam was in turn split into two components (ordinary and extraordinary waves) with equal amplitude in the nonlinear crystal.

Figure 3 : collision between two solitons in KTP crystal

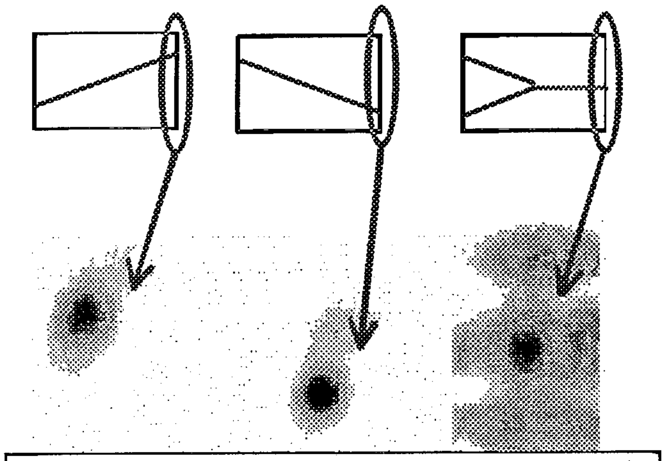


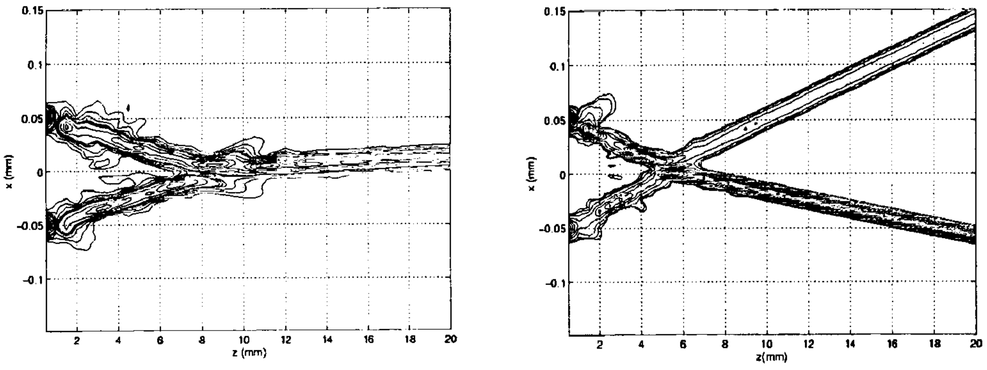
Figure-3 Recordings of the infrared beams at the output of the KTP crystal showing the switching and fusion of the quadratic solitons after their collision at small angle (<03 °)

The two beams at the input were separated by 100 μm and kept a width of 34 μm. Varying the position, d, of the WP with respect to the lens, allowed to obtain different input angles; from separating beams to colliding beams by passing through perfectly parallel beams configuration whilst keeping the initial separation of the two spots. Then we performed a set of experiments changing the position of WP and consequently the input angles Θ of the two beams.

Both beams were launched into the KTP crystal and the collision was slow enough to manifest its inelasticity. The output is in fact a single QSSW, since the two QSSWs fused at the coalescence point to generate a single self-guided beam (figure 3-C. When the tilt angle between the input beams was increased above Θ=0.4° we observed that the collision no longer lead to fusion but instead that the two QSSWs passed through each other without significant distortion. Figure A4 shows an example of quasi-elastic collision. In this case, $\Theta = 0.62°$, the collision inside the crystal is fast enough for the two QSSW to survive and to reappear after the collision point with small changes with respect to their properties before colliding.

Figure 4 provides the results of the numerical integration of the governing equation for an input condition close to the experimental situation. Although we have carried out the numerical integration in the 2D case, here, we present only the projection of the results into the (x,z) plane. Figure 4 shows the z-evolution of the extraordinary beam (ordinary exhibits the same behaviour and second harmonic follows adiabatically). We can note that the fundamental frequency at input generates the SH component to produce the QSSW well before the collision point. Here we can appreciate the mechanism of soliton fusion that takes place at the coalescence point where a new single QSSW is formed and radiative components are generated as well.

Figure 4 : numerical results



In conclusion we have reported the first experimental results on the collision between two dimensional QSSW with type two phase matching in a KTP crystal. By considering the collision between two orthogonally polarised QSSWs, we have proved that QSSWs can interact in a quasi elastic or in an inelastic fashion depending on the "velocity" of the collision. The experimental results have been described and reproduced by means of numerical integration of the governing equations. The observed phenomenon might find application in phase insensitive switching. Unfortunately, the soliton threshold close to ten Gigawatt/cm^2 is too high for telecommunication applications. To decrease this threshold we propose to use a PPLN cristal.

TWO-DIMENSIONNAL SELF-TRAPPED PROPAGATION (SOLITARY WAVE) IN PPLN CRYSTAL

Spatial solitary waves in PPLN have been recently predicted theoretically and numerically [4,5], but never observed experimentally. The goal of this part of the work was the experimental observation and characterization of spatial solitary waves in a PPLN crystal designed for SHG of 1064 nm. It was already experimentaly confirmed that PPLN, under mismatched SHG conditions, can give rise to strong Kerr-like self-phase modulation effects. An equivalent n2 coefficient as high as +/- 2.35. 10^{-13} cm^2/W was deduced from Z-scan measurements carried on a short crystal.

The experiments were carried with a Q-switched mode-locked Nd :YAG laser delivering 45 ps pulses with as much as few millijoule of energy. The laser beam of gaussian transverse profile was focused onto the entrance face of the uncoated PPLN sample to a spot of 22 µm diameter (FWHMI). The NL crystal was hold in a temperature regulated oven and heated to about 160°C to prevent from photorefractive effects induced by the second harmonic. The 14.5 mm propagation distance in the crystal represented approximately 6.5 diffraction lengths of the gaussian input beam. Like in most of the experiments on quadratic spatial soliton a single infrared pulse was launched in the crystal. The ideal situation for the excitation of a soliton would have required to send simultaneously a pulse at the second harmonic with the suitable relative intensity and phase. However even the simplest case of a single fundamental input leads at high intensity to a fast conversion of the input wave to the second harmonic. It has been calculated that the two fields then reach quickly a steady-state with propagation
distance corresponding to the spatial s O3 wafer (0.5 x 14.5 mm) was
carefully aligned with the optics axe PLN crystal was imaged with
magnification into a CCD camera co ere alternatively introduced to
R for the green outp d with the NL crystal tuned to
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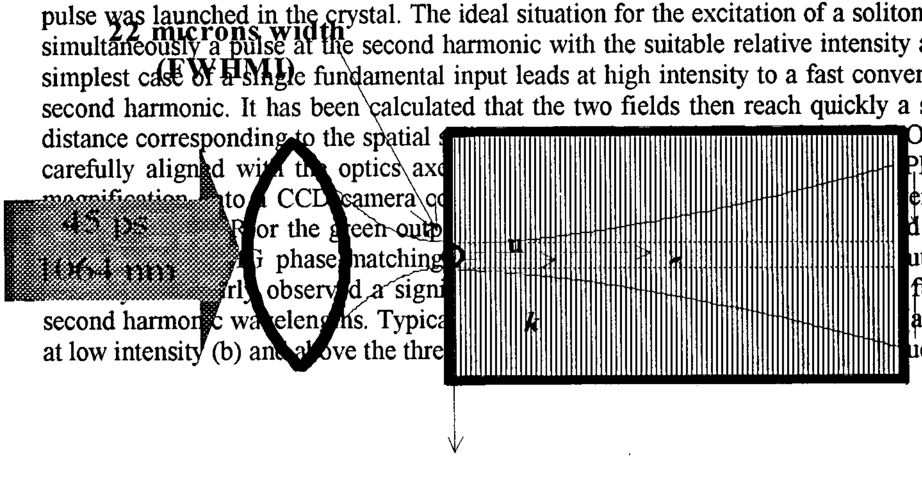
rly observed a signi fundamental as well as at the
second harmonic wavelengths. Typica a) and the outputs respectively
at low intensity (b) and above the thre uced on figure 5.



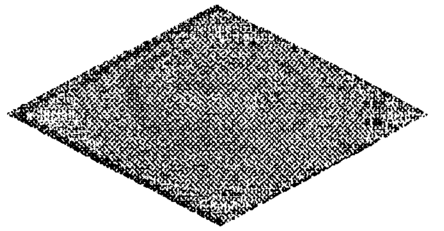
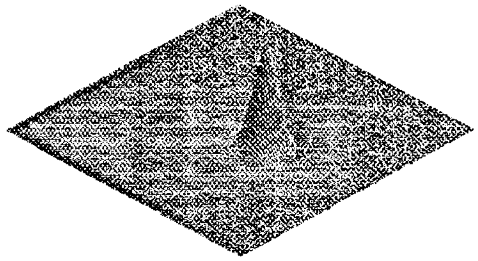
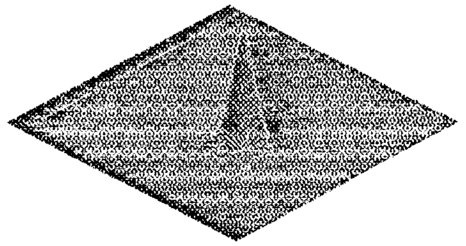


Figure 5 : input and output infrared beams for different intensities

The circular geometry of the input was preserved in the 2D quadratic solitary beam [6]. The fundamental wave started to self-focus at moderate intensity and was completely self-trapped for an intensity of 1.35 GW/cm^2. The self-trapping was maintained up to above four times this threshold. The intensities mentioned corresponded to the peak spatial and temporal values. By comparison a KTP crystal for a comparable input required a peak irradiance for reaching soliton propagation about 10 times greater than with PPLN (10 GW/cm^2). On the other hand the effective nonlinear parameter was measured on our 14 mm long PPLN sample to be approximately 17 pm/V which was more than five time greater than KTP (d_{eff}=3.3 pm/V). From the scaling law of the coupled wave equations one can deduce that the intensity threshold for soliton propagation is proportional to d_{eff}^{-2}. Consequently on the basis of the previous value published for a QSS in KTP we expected a soliton threshold of only 0.4 GW/cm^2 which is three times less than the measured value. The origin of this discrepancy is not known. It should not arise from crystal poling imperfections, for example random shift of the poling duty cycle or mark-to-space variation, since this is already included in the measured effective nonlinearity. We studied the variation in QSS intensity threshold with respect to a change in size of the input spot. The threshold was defined here as the intensity giving an output width no larger than 20% to that of the input. In agreement with theoretical.





QUADRATIC SOLITONS COLLISION AND SWITCHING IN PPLN

After the success of the excitation of soliton self-guided propagation in two transverse dimensions in the PPLN crystal fabricated at ORC we have tried to reproduce the investigation on quadratic soliton collision and fusion previously carried on a KTP crystal. The experimental arrangement was identical to the one depicted in figure 2. The collision angle between the two beams launched in the nonlinear crystal was modified by moving the wollaston prism along the optics axis of the set-up. The two gaussian input beams were still with a 22 microns width and were separated by a distance of about 200 microns on the input face of the crystal. Their intensity was adjusted to be balanced and then increased to reach the soliton (self-guided) regime. We have recorded the evolution of the infrared field cross-section at the output when the collision angle θ was increased. Typical images are displayed on an horizontal scale in figure 6. The two quadratic solitons appear as two vertical bright spots. The following images show the collision and fusion of the two solitons. Images of the linear output (at low intensity-no self-trapping) are given in Figure 6-A for comparison.

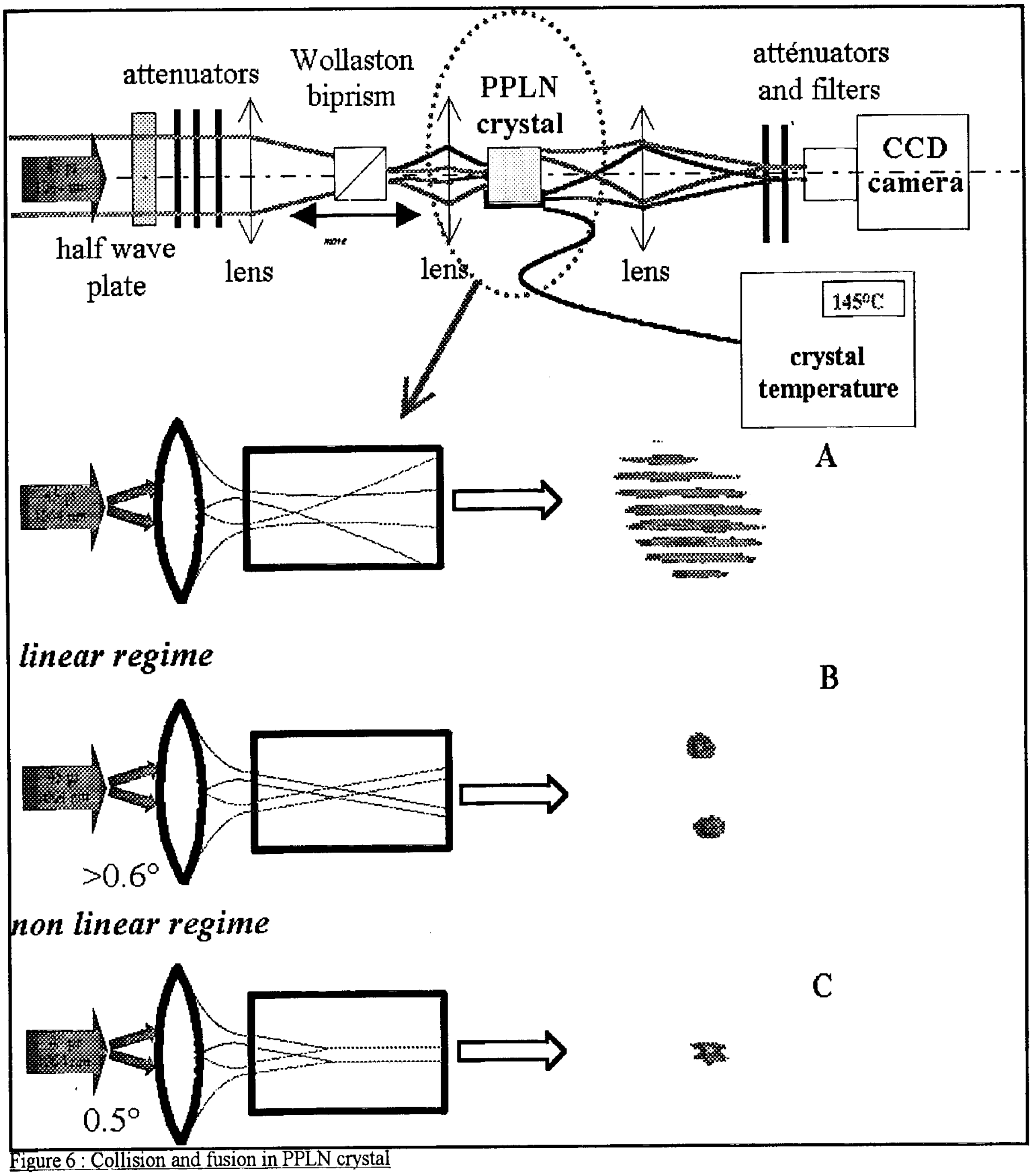


Figure 6 : Collision and fusion in PPLN crystal

In order to observe the fusion into a single beam of the two input waves after their collision the angle separation between the two wavevectors must be less than 0.6°. This value is larger than the one deduced from the previous experiments we have carried in a KTP crystal (0.3°). The difference may be explained by (i) the lack of walk-off in PPLN on the contrary to KTP that was cut for type II critical phase-matching and (ii) by the fact that the two inputs have a parallel polarisation. In a last experiment we have recorded the image of the output beam when one of the two input pulses was blocked by a screen at the input (a single soliton was excited) and when the two pulses collide and are being trapped into a single beam switched on a new transverse position. The corresponding patterns are shown on figure 7. The recorded images clearly show that we were able to reproduce quadratic spatial soliton collision and fusion (under appropriate condition) in a PPLN crystal. The compatibility between the all-optical switching process based on solitary waves and the efficient LiNbO3 crystal with periodic poling has been clearly demonstrated.

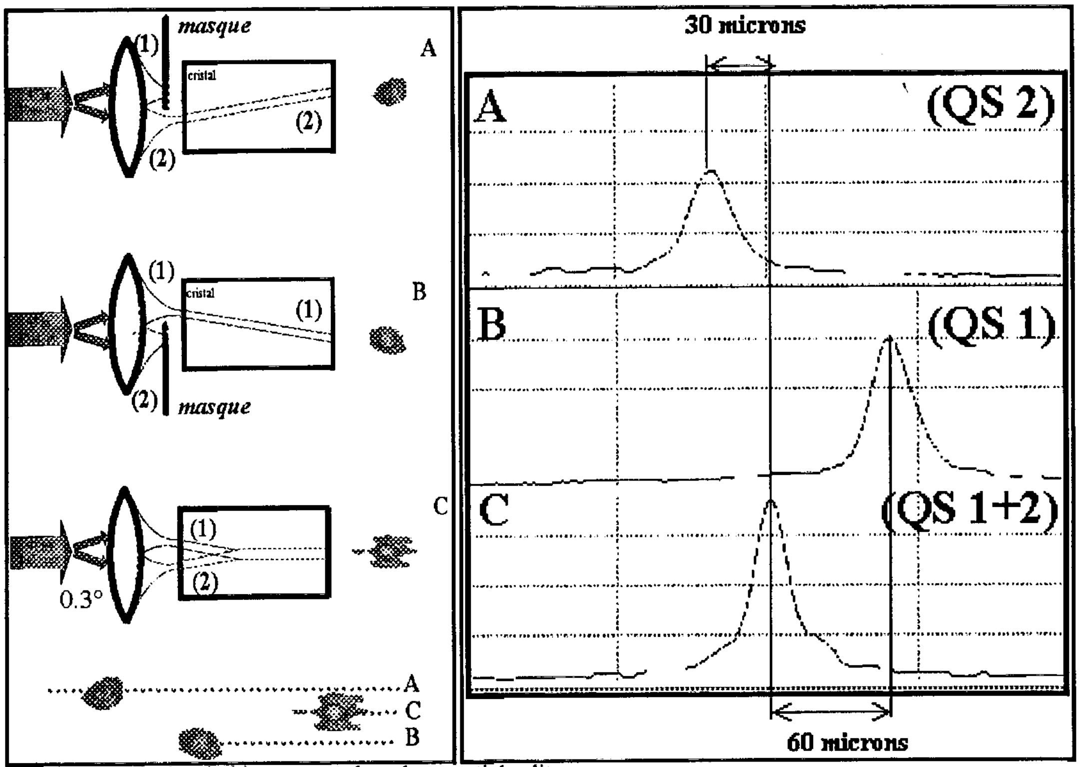


Figure 7 All optical switching process based on spatial solitons

PROCESSING SPEED

The speed of a device based on quadratic solitons is principally limited by the group velocity difference between the fundamental and second harmonic waves. This parameter obviously depends on the crystal characteristics. We may define the maximum processing speed as corresponding to the case where fundamental and harmonic pulses are separated at the output by a delay equal to their duration (FWHMI). Then for data at 1550nm wavelength, a device based on a PPLN crystal with a length identical to the one used in the experiments reported here, could route signals up to 220Gbit/s. In the case where fusion could be obtained on a 10mm long crystal then the processing speed should reach a value of 330Gbit/s. A device based on a KTP crystal should be of even greater capability. With a crystal length of the order of 15mm data flow of up to 1000Gbit/s could be processed at the expense of a higher switching power since its effective nonlinear coefficient is lower than that of PPLN. A second drawback comes from the critical phase-matching conditions leading here to a rather high walk-off angle (2.7°). In case of a strong interest for very high speeds, the best could be to keep the KTP crystal for its weak dispersion and use periodic poling for phase-matching to avoid the bad influence of the birefringence and take advantage of the highest nonlinear coefficient (d33=10.7 pm/V). Up to know we have considered the processing speed as limited by the linear features of the quadratic nonlinear crystals ie. their group velocity mismatch under second harmonic generation conditions. This is the worst situation since the strong interaction during propagation between the fundamental and harmonic pulses may give rise to a temporal confinement comparable to what happens in the space domain. Like the birefringence walk-off that can be cancelled when the spatial soliton regime is reached, the temporal walk-off can be also compensated in some situation of weak velocity mismatch leading to what has been called a "walking soliton". This assumption is plausible but remains to be demonstrated. If true this should ensure that the processing speed would no longer be limited on a QSS based device.

SWITCHING ENERGY

The switching energy corresponds to the energy required for formation of a quadratic spatial soliton. It depends on the duration of the excitation and on the soliton peak intensity that in turn evolve with the input beam width and wavelength, with the crystal refractive index and effective nonlinearity. In our experiment the soliton energy was fixed by the available crystal length, effective nonlinear coefficient, and laser characteristics. The lowest switching energy was measured to be about one microjoule with PPLN and about ten times more with KTP at a wavelength of 1064nm. In order to minimise the soliton energy we must use the shortest pulse, a wide beam, a crystal with the highest nonlinearity, a short wavelength. However we must keep in mind that for soliton propagation to take place the crystal length must be larger than the Rayleigh range of the input beam and even more for collision and fusion (crystal length > 5 x Rayleigh length). On a practical point of view it seems not reasonable and often not feasible to have access to crystal longer than few centimetres. So this fixes a upper limit to the soliton width (the lower limit is given by the damage threshold of the crystal). The shortest duration needed to preserve a spatial soliton regime is dictated by the group velocity mismatch. Consequently the lowest switching energy accessible with a PPLN based routing device would be of 100 nanojoule if no temporal self-trapping occurs. On the contrary in case of compensation of the group velocity mismatch by the nonlinear interaction the energy required for switching could be decreased to few nanojoule. Losses were supposed to be negligible in this approach.

WAVEGUIDES

A further reduction in the switching energy can be obtained by the use of a planar waveguide geometry that would confine the optical radiation in one of the two transverse dimensions allowing the beams to freely evolve only along the perpendicular dimension. Low loss single transverse mode PPLN and KTP waveguides have already been demonstrated by several research groups in the world. Using such component, the energy needed for QSS could be again reduced by one order of magnitude to fall into the picojoule range.

In conclusion a processing speed greater than 40 Gbit/s (even 200 Gbit/s) is clearly accessible to the device investigated here which is based on the collision and fusion of quadratic spatial solitons. Concerning the required switching energy, a value as low as few nanojoules is reachable provided short pulses are used for the generation of QSS, and if temporal self-trapping occurs between the fundamental and second-harmonic waves (which remains to be experimentaly demonstrated). The lowest energy will require a planar waveguide geometry.

CONCLUSION

First we have developed theoretical models to predict the evolution of the spatial soliton intensity threshold with respect to practical parameters. Subsequently we have confirmed the validity of our approach by several experimental measurements. Secondly we have proved that our idea can work with a well known common material a KTP crystal. We have experimentally demonstrated that soliton collision and fusion lead to a space switching of time synchronised pulses allowing ultrafast demultiplexing or routing of optical data. We have demonstrated experimentally that self-trapped propagation (spatial soliton) is possible in PPLN and quantified the advantage of choosing this material in terms of power threshold, and speed. We have reproduced the collision and fusion of solitons observed in KTP in the specific PPLN substrate.The frequency rate of the processing as well as the power level required to do it has been discussed in a last part.

For convenience the PPLN devices have been designed and operated at 1064 nm, and have followed initial experiments using standard commercially available KTP crystals to investigate soliton propagation and interaction. In the second phase the exploitation of the principle could be shifted to standard optical communications windows (1.3-1.5 microns) where the two types of crystal employed in the study should still remain the most efficient. Two questions have been raised after this first series of investigation. The first one concerns the possible temporal self-trapping between fundamental and harmonic pulses that could accompany the quadratic spatial soliton propagation. This point needs to be studied both theoretically and experimentally in order to determine the shortest pulse duration that remains compatible with soliton propagation. This parameter has a direct influence on the switching energy and ultimate processing speed of the proposed device. The second question is related to the wavelength selectivity of the interaction between the spatial solitons. This question merits to be investigated in depth at least theoretically. Finally in order to appreciate experimentally the advantage, in term of power threshold of a nonlinear planar waveguide it should be important to demonstrate that quadratic spatial soliton interaction may be effectively realised in a PPLN planar waveguide at a lower energy than in a bulk crystal. Extinction ratio of the commutation would be also characterised. Thes results confirm that PPLN structures (already proposed for a variety of advanced photonic switching applications [7]) are among the most promising materials for all-optical processing by use of quadratic nonlinearities.

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